REMOTE SENSING OF LAND USE AND LAND COVER

PRINCIPLES AND APPLICATIONS

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EDITED BY
CHANDRA P. GIRI

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Series Preface

Land cover describes both natural and man-made coverings of the Earth's surface, including biota, soil, topography, surface and groundwater, and human structures. A related concept is land use, referring to the manner in which the biophysical attributes of the land are manipulated and the purpose for which the land is used. Remote sensing is a cost-effective technology for mapping land cover and land use and for monitoring and managing land resources. The remote sensing literature shows that a tremendous number of efforts has been made for mapping, monitoring, and modeling land cover and land use at the local, regional and global scales. However, a comprehensive book has not been published to specifically address the issues of land cover science, mapping techniques and applications, and future opportunities. *Remote Sensing of Land Cover: Principles and Applications* uniquely fills this niche.

I am pleased that Dr. Chandra Giri, a research physical scientist at the United States Geological Survey, has taken the initiative to compile this volume. Contributed by a group of leading and well-published scholars in the field, this book first discusses—following a nice overview chapter by Dr. Thomas Loveland—the principles of land cover mapping, monitoring, and modeling. The second part of the book deals with case studies, mostly examined at the continental scale, from all over the world. Last but not the least, land cover programs supported by NASA and GEO (Group on Earth Observation) are introduced, providing a prospect for future national and international efforts. Dr. Giri carefully selected and examined each contribution and created a well-structured volume in order to address the issues of land cover from the viewpoints of science, technology, practical application and future needs. This comprehensive approach presents the readers with both a systematic view of the field and a detailed knowledge of a particular topic.

Like other books in the Taylor & Francis Series in Remote Sensing Applications, this book is designed to serve as a guide or reference for professionals, researchers, and scientists, as well as a textbook or an important supplement for teachers and students. I hope that the publication of this book will further promote a better use of Earth observation data and technology and will facilitate the assessing, monitoring, and managing of land resources.

Qihao Weng, PhD
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Preface

Land-cover characterization, mapping, and monitoring are the most important and typical applications of remotely sensed data. The availability and accessibility of accurate and timely land-cover datasets play an important role in many global change studies. Several national and international programs have emphasized the increased need for better land-cover and land-cover change information at local, national, continental, and global scales. These programs, such as the International Geosphere–Biosphere Program (IGBP), U.S. Climate Change Science Program, Land Cover and Land Use Change (LCLUC) program of the National Aeronautics and Space Administration (NASA), Global Land Project, Global Observation of Forest and Land Cover Dynamics (GOFC/GOLD), and Group on Earth Observations (GEO), have been in the forefront of framing scientific research questions on land-change science.

Recent developments in earth-observing satellite technology, information technology, computer hardware and software, and infrastructure have helped produce land-cover datasets of better quality. As a result, such datasets are becoming increasingly available, the user base is ever widening, application areas are expanding, and the potential for many other applications is increasing. Despite such progress, a comprehensive book, such as *Remote Sensing of Land Use and Land Cover: Principles and Applications*, on this topic has not been available so far. This book aims at providing a synopsis of basic land-cover research questions and an overview of remote-sensing history. It also offers an overview of land-cover classification, data issues, preprocessing, change analysis, modeling, and validation of results.

Examples of application at global, continental, and national scales from around the world have been provided. Overall, the book highlights new frontiers in remote sensing of land use/land cover by integrating current knowledge and scientific understanding and provides an outlook for the future. Specific topics emphasize current and emerging concepts in land-use/land-cover mapping, an overview of advanced and automated land-cover interpretation methodologies, and a description and future projection of the major land-cover types of the world. The book offers a new perspective on the subject by integrating decades of research conducted by leading scientists in the field.

The book is expected to be a guide or handbook for resource planners, managers, researchers, and students at all levels and a valuable resource for those just starting out in this field or those with some experience in the area of land-use/land-cover characterization and mapping. The book also contains some advanced topics useful for seasoned professionals. It can also be used as a textbook or as reference material in universities and colleges.

Chandra P. Giri
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Acknowledgments

I extend my heartfelt thanks to all the authors who have contributed to this book despite their busy schedule and workload. Besides thanking of my colleagues at work and throughout the world, who inspired me to work on this book, I express my deepest appreciation to the reviewers who offered critical comments and suggestions to improve the book. Finally, I thank my mother Rupa, wife Tejaswi, daughter Medhawi, and son Ash for their continued support and encouragement. I hope this book will help students and professionals who use remote-sensing technology for land-cover characterization, mapping, and monitoring.

The names of the reviewers are listed below alphabetically:

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Editor

Chandra P. Giri received his BS in forest conservation from Tribhuvan University, Nepal, his MS in interdisciplinary natural resources planning and management, and his PhD in remote sensing and geographic information systems from the Asian Institute of Technology (AIT), Bangkok, Thailand. Currently a research physical scientist at the U.S. Geological Survey (USGS)/Earth Resources Observation and Science (EROS) Center, he is also a guest/adjunct faculty at South Dakota State University. Earlier, he had worked for Columbia University's Center for International Earth Science Information Network (CIESIN), United Nations Environment Programme (UNEP), AIT, and Department of Forests, Nepal. At EROS, he leads the International Land Cover and Biodiversity program. His work focuses on global and continental-scale land-use/land-cover characterization and mapping using remote sensing and geographic information systems (GIS). His recent research was on global mangrove forest-cover mapping and monitoring using earth-observation satellite data, and on studying the impact, vulnerability, and adaptation of sea-level rise to mangrove ecosystems, integrating both biophysical and socioeconomic data. He is also researching the development of remote-sensing–based state-of-the-art methodologies to monitor carbon stocks for the Reducing Emissions from Deforestation and Forest Degradation (REDD) initiative. He has experience working in the private sector, academia, government, and international organizations at national, continental, and global levels in different parts of the world. He serves as an expert in national and international working groups. He has more than 50 scientific publications to his credit and has received several awards from USGS, NASA, and other organizations.

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Section I

Overview

1 Brief Overview of Remote Sensing of Land Cover

Chandra P. Giri

CONTENTS

1.1 BACKGROUND

Land cover of the earth's land surface has been changing since time immemorial and is likely to continue to change in the future (Ramankutty and Foley, 1998). These changes are occurring at a range of spatial scales from local to global and at temporal frequencies of days to millennia (Townshend et al., 1991). Both natural and anthropogenic forces are responsible for the change. Natural forces such as continental drift, glaciation, flooding, and tsunamis and anthropogenic forces such as conversion of forest to agriculture, urban sprawl, and forest plantations have changed the dynamics of land-use/land-cover types throughout the world.

In recent decades, anthropogenic land-use/land-cover change has been proceeding much faster than natural change. This unprecedented rate of change has become a major environmental concern worldwide. As a result, almost all ecosystems of the world have been significantly altered or are being altered by humans, undermining the capacity of the planet's ecosystems to provide goods and services. Two main forces responsible for anthropogenic changes are technological development and the burgeoning human population (Lambin and Meyfroidt, 2011).

Land-cover changes play a significant role in the global carbon cycle, both as a source and a sink (Loveland and Belward, 1997a; Moore, 1998), and in the exchange of greenhouse gases between the land surface and the atmosphere. For example, deforestation releases carbon dioxide into the atmosphere and changes land-surface albedo, evapotranspiration, and cloud cover, which in turn affect climate change and variability. In contrast, afforestation and reforestation remove carbon from the atmosphere (sink). Recent evidence shows that human-induced changes in land use/land cover over the last 150 years have led to the release of an enormous amount of carbon into the atmosphere. Although combustion of fossil fuels is the dominant source of release of carbon into the atmosphere, land use still contributes a significant portion (~20%) of anthropogenic emission, particularly in tropical areas.

Land-cover and land-use changes may have positive or negative effects on human well-being and can also have intended or unintended consequences (DeFries and Belward, 2000; Hansen and DeFries, 2004). Conversion of forests to croplands had provided food, fiber, fuel, and a host of other products to an increasing human population throughout human history. At the same time, tropical deforestation has reduced biodiversity, degraded watersheds, increased soil erosion, and consequently raised the risk of unintended but devastating forest fire. Owing to the rapid and unprecedented land-use/land-cover change in recent years, negative consequences such as soil erosion, loss of biodiversity, water pollution, and air pollution have increased. The benefits and economic gains provided by ecosystems have started eroding because these benefits are derived at the expense of degradation of the ecosystem.

1.2 RESEARCH NEED, PRIORITIES, AND OPPORTUNITIES

Understanding the distribution and dynamics of land cover is crucial to the better understanding of the earth's fundamental characteristics and processes, including productivity of the land, the diversity of plant and animal species, and the biogeochemical and hydrological cycles. Assessing and monitoring the distribution and dynamics of the world's forests, shrublands, grasslands, croplands, barren lands, urban lands, and water resources are important priorities in studies on global environmental change as well as in daily planning and management. Information on land cover and land-cover change is needed to manage natural resources and monitor global environmental changes and their consequences (Loveland and Belward, 1997b).

Several national and international programs have emphasized the increased need for better land-cover and land-cover change information at local, national, continental, and global levels. These programs, such as International Geosphere Biosphere Program (IGBP), U.S. Climate Change Science Program, Land Cover and Land Use Change (LCLUC) program of the National Aeronautics and Space Administration (NASA), Global Land Project, Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD), and Group on Earth Observations (GEO), have been in the forefront of scientific inquiry in land-change science. For example, GOFC-GOLD has provided detailed guidelines for land-cover products (Turner et al., 1994). Similarly, the GEO has identified key land-cover observations and desired products that are likely to contribute to specific areas of societal benefits (Figure 1.1). Land-cover observation and monitoring can provide critical information needed for several GEO areas of societal benefits (Table 1.1).

In essence, the GEO has (1) highlighted the societal needs and relevance of land observations, (2) provided a forum for advocating global land-cover and change observations as a key issue, (3) fostered integrated perspectives for continuity and consistency of land observations, (4) helped evolve and apply international standards for land-cover characterization and validation, (5) improved a shared vision within the land observation community and involved global actors, (6) advocated joint participation in ongoing global mapping activities, regional networking, and capacity building in developing countries, and (7) helped develop international partnership involving producers, users, and the scientific community to better produce and use existing datasets (http://www.geogr.uni-jena.de/~c5hema/telecon/geo_achievement_global_land_cover.pdf).

Similarly, the United States Global Change Research Program (USGCRP) have identified five strategic questions that are important for future research on land cover and land-cover change (http://www.usgcrp.gov/usgcrp/ProgramElements/land.htm).

1. What tools or methods are needed to better characterize historical and current land-use and land-cover attributes and dynamics?
2. What are the primary drivers of land-use and land-cover change?
3. What will land-use and land-cover patterns and characteristics be in 5–50 years?
4. How do climate variability and change affect land use and land cover, and what are the potential feedbacks of changes in land use and land cover to climate?
5. What are the environmental, social, economic, and human health consequences of current and potential land-use and land-cover change over the next 5–50 years?

Townshend et al. (2011) identified major stakeholders of global land observations that are relevant to land-cover observations and monitoring. They are as follows:

- National, regional, or local governments that need the information to assist them in developing and implementing their policies and to help them meet mandatory reporting requirements resulting from such policies

FIGURE 1.1 **(See color insert.)** Nine areas of societal benefit of the Group on Earth Observations (GEO).

- International initiatives to help develop and fund programs for countries that need the information to develop their policies and operational strategies
- Nongovernmental organizations
- Scientists who need the information to improve our understanding of the processes and uncertainties associated with the earth system
- The individual citizen who needs understandable and reliable information on global environmental trends
- The private sector that needs information to help partner and directly service the previous five stakeholders

With the recent advancement in remote sensing and geographic information systems (GIS) and computer technology, it is now possible to assess and monitor land-use/land-cover changes at multiple spatial and temporal scales (Hansen and DeFries, 2004). For example, the National Land Cover Database (NLCD) 2011 is an integrated database encompassing land-cover and land-cover change products at various thematic, spatial, and temporal resolutions (Figure 1.2).

Remote sensing offers several advantages. It is a relatively inexpensive and rapid method of acquiring up-to-date information over a large geographical area owing to its synoptic coverage and repetitive measurements. Remote-sensing data usually acquired in digital form are easier to manipulate and analyze; they can be acquired not only from visible but also from spectral ranges that are invisible to human eyes; they can be acquired from remote areas where accessibility is a concern; and they provide an unbiased view of land use/land cover. Similarly, historical data date back as early as the 1970s, and such data are becoming freely available. Several remotely sensed

TABLE 1.1
Linking the GEO Areas of Societal Benefits with Global Land-Cover Observation and User Requirements

GEO Areas of Societal Benefits	Key Land-Cover Observations and Desired Products
Disasters: reducing loss of life and property from natural and human-induced disasters	Fire monitoring (active + burn); surface-cover type changes and land degradation due to disasters; location of population and infrastructure
Health: understanding environmental factors affecting human-induced disasters	Land characteristics/change for disease vectors; land cover/change affecting environmental boundary conditions; demographics, socioeconomic conditions, and location and extent of settlement patterns
Energy: improving management of energy resources	Biofuel production sustainability; biomass yield estimates (forestry and agriculture); assessments for wind and hydropower generation and explorations
Climate: understanding, assessing, predicting, mitigating, and adapting to climate variability and change	Greenhouse gas emissions as the cause of land-cover change; land-cover dynamics forcing water and energy exchanges; location and extent of energy combustion
Water: improving water resources management through better understanding of the water cycle	Land-cover change affecting the dynamics of the hydrological systems; available water resources and quality distribution of water bodies and wetlands; water-use pattern (i.e., irrigation and vegetation stress) and infrastructure
Weather: improving weather information, forecasting, and warning	Land-cover change affecting radiation balance and sensible heat exchange; land surface roughness; biophysical vegetation characteristics and phenology
Ecosystems: improving the management and protection of terrestrial, coastal, and marine ecosystems	Changes in environmental conditions, conservation and provision of ecosystem services; land-cover and vegetation characteristics and changes; land-use dynamics and driving processes
Agriculture: supporting sustainable agriculture and combating desertification	Distribution and monitoring of cultivation practices and crop production; forest types and changes (e.g., logging); land degradations, and threats to terrestrial resources and productivity
Biodiversity: understanding, monitoring, and observing biodiversity	Ecosystem characterization and vegetation monitoring (types and species); habitat characteristics and fragmentation of invasive and protected species; changes in land cover and use affecting biodiversity

Source: Group on Earth Observations. Geo portal, http://www.geoportal.org.

data are available for assessing and monitoring land cover. A list of primary remote-sensing systems used for observing and monitoring land cover and land use is presented in Table 1.2.

Land use is difficult to observe because the intended use of the land may be different from the actual use. What we see are the physical artifacts of that use. For example, forest in many countries is defined as land designated as forest by the government regardless of whether the land is covered by trees or not. From a land-cover perspective, it could be barren land if the area is not covered by trees. Some land-use types such as industrial areas can be observed and measured using remotely sensed data, particularly with the help of very high-resolution satellite data, aerial photographs, ancillary data, and/or *a priori* knowledge. Certain land-use types can be derived from observed land-cover types because the realms of land use and land cover are interconnected. Observing land use using remotely sensed data becomes complicated when a single land-cover class is associated with multiple uses and multiple land-cover types are used for a single use. For example, a forest land cover can be used for timber production, fuel-wood production, recreation, biodiversity conservation, religious

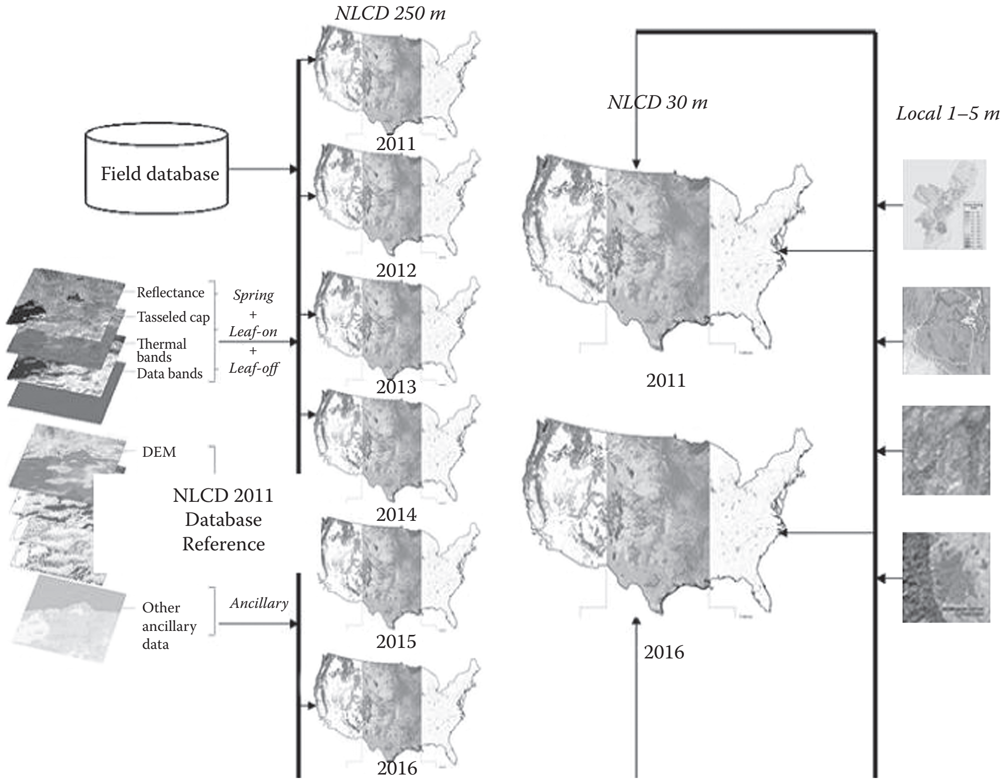

FIGURE 1.2 **(See color insert.)** A potential product framework proposed for NLCD 2011. (Adapted from Xian, G., Homer, C., and Yang, L., 2011. Development of the USGS National Land-Cover Database over two decades. In: Weng, Q. H., ed., *Advances in Environmental Remote Sensing—Sensors, Algorithms, and Applications.* CRC Press, Boca Raton, FL, 525–543.)

purposes, hunting/gathering, shifting cultivation, watershed protection, soil conservation, and carbon sequestration. Furthermore, several land-cover types such as croplands, grasslands, woodlots, and settlements can be used for a certain farming system (Meyer and Turner, 1992).

However, remote sensing of land cover may have many limitations. Data availability, accessibility, and cost of remotely sensed data may be an issue particularly in developing countries. However, since 2008, the U.S. Geological Survey/Earth Resources Observation and Science Center (USGS/EROS) has been providing free terrain-corrected and radiometrically calibrated Landsat data. Other space agencies and data providers are expected to follow suit. Much needs to be done to improve the preprocessing and classification accuracy of satellite imagery. Recently, the NASA-funded Web-Enabled Landsat Data (WELD) project demonstrated that large-scale (e.g., conterminous United States), cloud-free, and radiometrically and atmospherically corrected Landsat mosaics at 30-m resolution can be produced using the entire Landsat archive. The advantage is that "users do not need to apply the equations and spectral calibration coefficients and solar information to convert the Landsat digital number to reflectance and brightness temperature, and successive products are defined in the same coordinate system and align precisely, making them simple to use for multitemporal applications" (http://globalmonitoring.sdstate.edu/projects/weld/). The WELD product can then be used for land-cover characterization, mapping, and monitoring. At times, classification results may not be repeatable, and classification accuracy may be too low. Skilled manpower needed for the analysis may not be available. Incorporating field inventory data is critical for classification and validation.

Land-use/land-cover characterization and mapping is one of the most popular applications of remotely sensed data. Significant advances have also been made in the application of remote sensing

TABLE 1.2
List of Major Remote-Sensing Systems Used for Observing and Monitoring Land Cover and Land Use

Satellite	Web Site	Satellite	Web Site
ALOS/AVNIR/PRISM	http://www.jaxa.jp/projects/sat/alos/index_e.html	*MERIS (Envisat)*	http://envisat.esa.int/
ASTER	http://envisat.esa.int/	*MODIS*	http://modis.gsfc.nasa.gov/
CARTOSAT-1	http://www.isro.org/	*OrbView-3*	http://www.geoeye.com/
CBERS-1, 2, 2B	http://www.cbers.inpe.br/	*Quickbird*	http://www.digitalglobe.com
DMC	http://www.dmcii.com/	*RapidEye1–5*	http://www.rapideye.de/
EROS-A, EROS-B	http://www.imagesatintl.com	*SPOT 1–5*	http://www.spotimage.fr
FORMOSAT-2	http://www.spotimage.fr	*THEOS*	http://new.gistda.or.th/en/
GeoEye-1	http://launch.geoeye.com/LaunchSite/	*WorldView-1*	http://www.digitalglobe.com/
GOSAT	http://www.jaxa.jp/projects/sat/gosat/index_e.html	*WorldView-2*	http://worldview2.digitalglobe.com/about/
IKONOS	http:/ /www.geoeye.com	*ASAR(Envisat)*	http://envisat.esa.int/
IRS-1A, 1B,1C, 1D	http://www.isro.org	*COSMO-SkyMed 1–3*	http://www.telespazio.it/cosmo.html
IRS-P2, P3, P4	http://www.isro.org	*ERS-1, ERS-2*	http://www.esa.int/esaCP/index.html
KOMPSAT-1	http://new.kari.re.kr/english/index.asp	*PALSAR*	http://www.jaxa.jp/index_e.html
KOMPSAT-2	http://earth.esa.int/object/index.cfm?fobjectid=5098	*RADARSAT-1, 2*	http://gs.mdacorporation.com/
Landsat 1–5, 7	http://landsat.gsfc.nasa.gov/	*TerraSAR-X*	http://www.astrium-geo.com/en/228-terrasar-x-technical-documents

Source: Adapted from Remote sensing satellites. http://www.remotesensingworld.com/2010/06/16/remote-sensing-satellites/. With permission.
Note: This table is not intended to be complete.

for land-cover and land-use characterization, mapping, and monitoring to support global environmental studies and resource management. However, further work is needed not only for characterization and mapping but also for forecasting land-use/land-cover change for the future. Availability and accessibility of remotely sensed data are also critical. Scientific advancement in land-cover change analysis, accuracy assessment, use of multiscale data, addition of thematic richness (e.g., percent tree), and improved strategies for using land cover to more specifically infer land uses are needed (Loveland, 2004).

Looking ahead, the following were identified as the highest priority global land-cover issues (Townshend et al., 2011):

- Commitment to continuous 10–30-m resolution optical satellite systems with data acquisition strategies at least equivalent to that of the Landsat 7 mission.
- Development of *in situ* reference network for land-cover validation.
- Generation of annual products documenting global land-cover characteristics at resolutions between 250 m and 1 km, according to internationally agreed standards with statistical accuracy assessment.
- Generation of products that document global land cover at resolutions between 10 and 30 m at least every 5 years; a long-term goal is annual monitoring.
- Ensuring future continuity of mid-resolution multispectral SAR L-band data.
- Coordination of radar and optical data acquisitions so that radar data are usable to ensure regular monitoring of global land cover.
- Agreed upon internationally accepted land-cover and use classification systems.

The Ministry of Science and Technology of the People's Republic of China had approved the launching of a global land-cover mapping project to produce land-cover data products for 2000 and 2010, using Landsat, MODIS, and Chinese weather satellite data, with the minimum mapping unit of 30 m and the final product aggregated to 250 m. Similarly, the U.S. GEO announced the Global Land Cover Initiative at the Beijing GEO Ministerial Summit in November 2010, which aimed at the following:

1. Developing an initial global land-cover baseline for the 2010 period, using Landsat 30-m satellite data
2. Implementing an ongoing monitoring system that provides periodic (1, 2, 5 years) land-cover updates and land-cover change products from 2010 onwards
3. Improving the availability of 30-m class data (whenever possible)
4. Establishing the capability and capacity to develop historical land-change time series (1970s to present)

Significant progress in land-cover research has been made in the last two decades. With the development of remote sensing and computer technology, free availability of remotely sensed data, and availability of land-change expertise, a land-cover monitoring system is expected to be operational in the near future.

DEFINING LAND USE AND LAND COVER

Land use and land cover have often been confused and used interchangeably in the literature and also in daily practice. Thus, it is important to define and understand the meaning of these terms so that they can be used correctly, meaningfully, and to the best advantage. *Land cover* refers to the observed biotic and abiotic assemblage of the earth's surface and immediate subsurface (Meyer and Turner, 1992). Examples of major land-cover types are forests, shrublands, grasslands, croplands, barren lands, ice and snow, urban areas, and water bodies (including groundwater). As can be seen from the definitions and examples, the term now includes not only the vegetation that covers the land but also human structures, such as roads, built-up areas, and immediate subsurface features such as groundwater. *Land use* is defined as the way or manner in which the land is used or occupied by humans. In a nutshell, land cover represents the visible evidence of land use. A land covered by vegetation can be a forest as seen from the ground or through remote-sensing observations; however, the same tract of forest can be used for production, recreation, conservation, and religious purposes (Figure 1.3). In other words, land cover is the observed physical cover, whereas land use is based on function or the socioeconomic purpose for which the land is being used. A piece of land can have only one land cover (e.g., forests), but can have more than one land use (e.g., recreational, educational, and conservational).

LAND-COVER AND LAND-USE CHANGE

Land-cover change can be characterized as land-cover conversion and modification. Land-cover conversion is a change from one land-cover category to another, and modification is a change in condition within a land-cover category (Meyer and Turner, 1994). An example of the former is change from cropland to urban land, and an example of the latter is degradation of forests. Forest degradation may be due to change in phenology, biomass, forest density, canopy closure, insect infestation, flooding, and storm damage. Conversion is generally easier to measure and monitor than modification using remotely sensed data. Modification is usually a long-term process and may require multiyear and multiseasonal data for accurate quantification. Land-use change is a change in the use or management of land by humans. Land-use change may change without land-cover conversion or modification. For example, a production forest can be declared a protected area, and the number of visitors in a recreational forest may change without land-cover modification. On the contrary, land cover may change even if the land use remains unchanged; however, land-use change is likely to cause land-cover change.

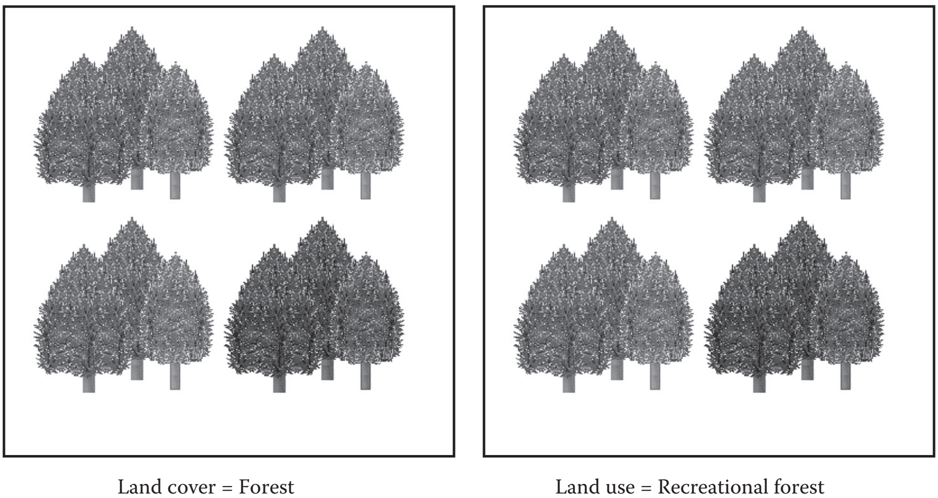

FIGURE 1.3 Land cover and land use.

1.3 ORGANIZATION OF THE BOOK

The book is divided into four sections (Figure 1.4). Each chapter is organized around two basic themes: land cover and remote sensing; the chapters describe the salient issues in remote sensing and in land cover and their applications. Section I begins with a brief overview of remote sensing of land cover and the history of land-cover mapping. It provides a brief overview of key issues, opportunities, and recent advancements in the interpretation of remotely sensed data for land cover. Significant improvements have been made in land-cover research over the years, but many challenges remain for operational land-cover observation and monitoring (Giri et al., 2005). The second chapter in this section provides a comprehensive overview of the history of land-cover mapping. Historical perspective is needed to understand the data, classification system, infrastructure, and institutional issues and priorities better. Lessons learned from past experiences will be valuable for future land-cover initiatives.

Section II provides the basic principles of remote sensing for land-cover characterization, mapping, and monitoring. It highlights the fundamental mapping concepts that need to be considered during land-cover mapping using remote-sensing data. A land-cover classification system, including semantic issues and interoperability, is critical for evaluation, comparison, and change analysis of land-cover products. At present, no definitive universally accepted land-cover classification exists (Townshend et al., 2011). However, the Land Cover Classification System (LCCS) is currently the most comprehensive, internationally applied, and flexible framework for land-cover characterization. Thus, it is important to examine how LCCS is useful in evaluating land-cover legends. The section also highlights data records (e.g., AVHRR and MODIS) that can be routinely applied to

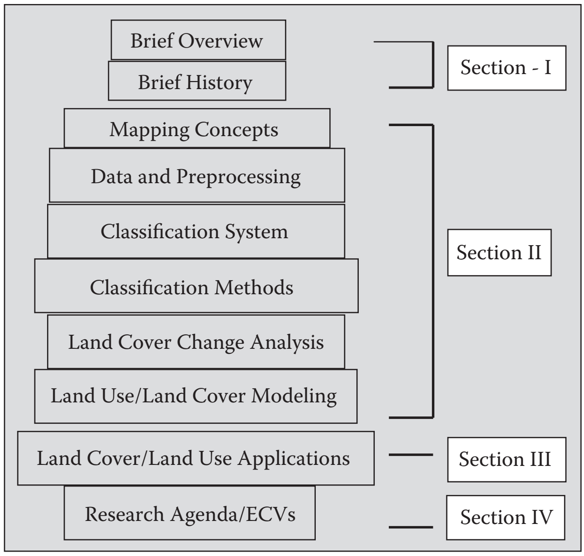

FIGURE 1.4 Main contents of the book.

study long-term changes in land-cover dynamics at multiple scales. Section II also addresses image-processing steps such as preprocessing, classification, change analysis, and validation of results. These chapters provide an overview of the science with examples. They also address the limitations and future possibilities of land-use/land-cover modeling in the United States.

Section III provides examples of land-cover application at global, continental, and national scales from around the world. Chapters in this section use multiple data sources and provide in-depth understanding of land cover and land-cover dynamics in multiple spatial, thematic, and temporal resolutions. Finally, Section IV highlights the research agendas for land-cover and land-use change and the importance of land cover as one of the major essential climate variables (ECVs). Recent research agendas and future research priorities from NASA's Land Cover and Land Use program are discussed. The final chapter also discusses how operational global and regional land-cover observations and monitoring are developed.

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Meyer, W.B. and Turner, B.L. 1992. Human-population growth and global land-use cover change. Annual Review of Ecology and Systematics, 23, 39–61. Brief History Data and Preprocessing Classification System Classification Methods Land Cover/Land Use Applications Land Cover Change Analysis Land Use/Land Cover Modeling Research Agenda/ECVs Mapping Concepts Brief Overview Section - I Section II Section III Section IV

FIGURE 1.4 Main contents of the book.

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Section II

Basic Principles

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8 Chapter 8: Preprocessing : Need for Sensor Calibration

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(a) (b) (c)

FIGURE 10.6 (See color insert.) Example of comparison between QuickBird image (a), supervised classi

cation of the image formed by the principal component and the NDVI index (b), and the HTM classi cation (c).

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Section III

Application Examples

16 Chapter 16: Operational Service Demonstration for Global Land-Cover Mapping : The GlobCover and GlobCorine Experiences for 2005 and 2009

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Section IV

Looking Ahead

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FIGURE 1.1 Nine areas of societal bene�t of the Group on Earth Observations (GEO). NLCD 250 m NLCD 30 m Local 1-5 m 2011 2016 2016 NLCD 2011 Database Reference 2015 2014 2013 2012 2011 Field database Reflectance Tasseled cap �ermal bands Data bands DEM Other ancillary data Ancillary Spring + Leaf-on + Leaf-off

FIGURE 1.2 A potential product framework proposed for NLCD 2011 (Adapted from Xian, G., Homer, C.,

and Yang, L., 2011. Development of the USGS National Land-Cover Database over two decades. In: Weng,

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Boca Raton, FL, 525–543.). “Similar disjoint” “Very different” West Chester 00 100 %100 % 0 100 % 0 100 % “Very similar” “Class/subclass”

FIGURE 3.4 An example of semantic land-cover change map using a bivariate color scheme to represent

different combinations of the semantic distance and overlap metric. 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0 0–25 25–50 50–75 50–100 100–200 200–300 300–400 min medi a max 0 Distance (m) Land cover “semantic variogram” cloud Distance (km) S e m a n t i c d i s t a n c e S e m a n t i c d i s t a n c e 0 5 0 0 , 0 0 0 1 , 0 0 0 , 0 0 0 1 , 5 0 0 , 0 0 0 2 , 0 0 0 , 0 0 0 2 , 5 0 0 , 0 0 0 3 , 0 0 0 , 0 0 0 3 , 5 0 0 , 0 0 0

FIGURE 3.5 Random sample points (n = 110) across a North American land-cover dataset are plotted in a

semantic variogram according to pair-wise comparison of spatial distance of the points and the semantic dif

ference between the land-cover classes at these points. Box plots summarize the points for speci�ed spatial

distance intervals.

100%

90%

80%

70%

60%

50%

40%

30%

20%

10% 11 14 20 30 40 50 60 70 90 Land-cover classes 100 110 120 130 140 150 170 180 190 200 11 - Irrigated cropland 14 - Rainfed cropland 20 - Mosaic cropland/natural vegetation 30 - Mosaic natural vegetation/cropland 40 - Closed to open broadleaved evergreen forest 50 - Closed broadleaved deciduous forest 60 - Open broadleaved deciduous forest 70

- Closed needleleaved evergreen forest 90 - Open needleleaved forest 100 - Closed to open mixed forest 110 - Mosaic forest or shrubland/grassland 120 - Mosaic grassland/forest or shrubland 130 - Shrubland 140 - Grassland 150 - Sparse vegetation 160 - Forest, regularly flooded 170 - Forest, permanently flooded 180 - Flooded grassland or woody vegetation 190 - Urban areas 200 - Bare areas 210 - Water bodies 220 - Snow and ice Class color codes

P r

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FIGURE 5.1 Classiﬁcation trajectories of the pixels that are not identically classiﬁed in the GlobCover 2005

and 2009 land-cover products. (From Bontemps, S. et al., GlobCover 2009—Products description and valida

tion report, version 2.0, 17/02/2011. Available at: http://ionia1.esrin.esa.int/. With permission.) Land cover over Africa GlobCover-VEGETATION 2008 0 500 1000 2000 km N 0 500 Land cover over Africa GlobCover-VEGETATION 2007 1000 2000 km N Spatial resolution: 1 km Spatial resolution: 1 km

FIGURE 5.2 Land-cover results obtained by the automated GlobCover classiﬁcation chain from 2007 to

2008 daily SPOT-Vegetation time series. (From Moreau, I., Méthode de cartographie globale de l’occupation

du sol par télédétection spatiale: Analyse de la stabilité interannuelle de la chaîne de traitement GlobCover,

mémoire de ﬁn d’études, Université Catholique de Louvain, Faculté d’ingénierie biologique, agronomique et

environnementale, 2009. With permission.)

TABLE 5.1

Illustration of the Proposed Concepts of Land-Cover Features and Land-Cover Conditions Land-cover features (permanent aspect or stable elements of the landscape) Land-cover condition (dynamic component of land cover) Features' nature: built-up Features' structure: high density of building Features' naturalness: arti￿cial Features' homogeneity: urban patterns made of a mixture of green areas, buildings, houses, and water channels Seasonal behavior of the green vegetation (NDVI pro￿le) Snow cover usually from December 15 to January 15 No ±ooding dynamic No §re dynamic Possible denomination of this land cover according to the following: A land-cover typology A: Urban area A land-cover typology B: Residential area A land-cover typology C: Impervious surface area Land-cover features (permanent aspect or stable elements of the landscape) Land-cover condition (dynamic component of the land cover) Features' nature: tree cover Features' structure: high tree density (canopy cover of 92%) Features' naturalness: natural broadleaved, evergreen vegetation Features' homogeneity: homogeneous canopy (few clearings) Slight seasonal behavior of the green vegetation (NDVI pro￿le) No snow dynamic No ±ooding dynamic No §re dynamic Possible denomination of this land cover according to the following: A land-cover typology A: Closed evergreen forest A land-cover typology B: Natural woody vegetation A land-cover typology C: Dense broadleaved forest 3 North American tundra Eurasian tundra 2 1 0 -1 -2 -3 1982 1986 (a) (b) (c) (d) 1991 1996 2001 2006 Year S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1 -2 -3 1982 1986 1991 1996 2001 2006 Year S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1 -2 -3 1982 1986 1991 1996 2001 2006 LAI NDVI Temperature Year North American needle-leaf forests Eurasian needle-leaf forests S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1 -2 -3 1982 1986 1991 1996 2001 2006 Year S t a n d a r d i z e d a n o m a l y

FIGURE 7.2 Standardized April-to-October anomalies of AVHRR LAI (green), GIMMS AVHRR NDVI

(blue), and GISS temperature (red dashed line) for Eurasian and North American needle-leaf forests (panels

[c] and [d]) and tundra (panels [a] and [b]) from 1982 to 2006. (From Ganguly, S. et al., Rem. Sens. Environ.,

112, 4318–4332, 2008a.)

60(a) (b) 30 20 10 0

50

40

30

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10

0 1 2 3 4 5 6 7 8 9 10 1 – Evergreen needleleaf forest 16 – Barren and sparsely vegetated 15 – Snow and ice 14 – Croplands/natural vegetation mosaic 13 – Urban and built-up 12 – Croplands 11 – Permanent wetlands 10 – Grasslands 9 – Savannas 8 – Woody savannas 7 – Open shrublands 6 – Closed shrublands 5 – Mixed forest 4 – Deciduous broadleaf forest 3 – Deciduous needleleaf forest 2 – Evergreen broadleaf forest 11 12 13 14 15 16 0 10 20 30 40 50 60 70 80 Bare Herbaceous Tree 90 100 Percentage coverLandcover type (IGBP)

FIGURE 7.4 Percentage distribution of IGBP land-cover classes (panel [a]) and frequency distribution of

bare (red), herbaceous (blue), and tree (black) cover from MODIS VCF map, expressed as percentage of total

number of pixels (panel [b]) for the peak annual NDVI climatology range of 0.12–0.55. Peak annual NDVI climatology 0 0.12 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55

FIGURE 7.3 Color map of peak annual NDVI climatology. Peak annual NDVI climatology was calculated by first estimating the 26-year (1981–2006) mean of monthly NDVI (monthly NDVI climatology) and then

selecting the maximum value (per pixel, from 12-monthly climatological NDVI values). A spatial mask was

applied on the color map based on peak annual NDVI climatology values in the range of 0.12–0.55. The NDVI

data used is the AVHRR GIMMS NDVI product. Decadal scale change in peak LAI (%) Decadal scale change in precipitation (%) -60 -40

(a)

(b) -20 0 20 40 60 -60 -40 -20 0 20 40 60

FIGURE 7.5 (a) Percentage change in mean peak annual LAI between decade 1 (1981–1990) and decade 2 (1995–

2006). For each year in a decade, the peak LAI was selected (per pixel from 12 LAI values). The mean peak LAI

was calculated for each decade. Finally, the percentage change was calculated as [100 × (mean peak LAI decade2

– mean peak LAI decade1)/(mean peak LAI decade1)]. A spatial mask was applied on the color map based on peak

annual NDVI climatology values in the range of 0.12–0.55 (all values outside this range appear in gray—masked

out). (b) Percentage change in mean peak annual precipitation (mm/year) between decade 1 (1981–1990) and decade

2 (1995–2006). Peak precipitation for each year was calculated by summing the precipitation in the three wettest

months. The mean peak annual precipitation for each decade and percentage change were calculated as in (a). 3 2 1 0 -1 -2 -3 1981 1986 1991 1996 Sahel(a) (b)

(c) (d) Southern Africa South East Asia Australia Year 2001 2006 S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1 -2 -3 1981 1986 1991 1996 Year 2001 2006 S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1 -2 -3 1981 1986 1991 1996 Year 2001 2006 S t a n d a r d i z e d a n o m a l y 3 2 1 0 -1

-2 -3 1981 1986 LAI NDVI Precipitation 1991 1996 Year 2001 2006 S t a n d a r d i z e d a n o m a l y

FIGURE 7.6 Standardized anomalies of annual peak AVHRR LAI (green line), annual peak AVHRR NDVI

(blue line), and annual peak (three wettest month CRU + TRMM) precipitation (red dashed line) for the semi

arid regions (panels [a]–[d]) from 1981 to 2006. 100(a) Groundwater Cropped area 80 60 40 20 0 100 I r r i g a t e d f r o m g r o u n d w a t e r (%) 80 60 40 20 0 C r o p p e d a r e a i r r i g a t e d (%) A n d h r a P r a d e s h A s s a m N A B i h a r G u j a r a t H a r y a n a K a r n a t a k a K e r a l a M a d h y a P r a d e s h M a h a r a s h t r a O d i s h a P u n j a b R a j a s t h a n T a m i l N a d u U t t a r P r a d e s h W e s t B e n g a l

FIGURE 7.9 (a) Percentage of cropped area that is irrigated (blue bar) and percentage of irrigated land utiliz

ing groundwater (green bar) for each of the major Indian states. –100 –50 0 50 100 Onset of greenness anomalies Growing-season length anomalies 2 1.5 × 10 5 0.5 0 –100 –50 0 50 100 Green-up anomaly F r e q u e n c y 1 2 1.5 0.5 0 –100 –50 0 50 100 Growing-season length anomaly F r e q u e n c y 1

FIGURE 7.11 Anomalies in the timing of green-up onset and growing-season length for 2002 relative to the

2001–2006 mean. Histograms show the frequency of green-up and growing-season length anomalies. Details

about processing the MODIS data and deriving the phenological parameters have been described in depth by

Ganguly et al. (2010). (a) (b)

FIGURE 9.2 (a) Landsat 5 image, WRS2 path/row 024/032, centered on 91 10 21.5W, 39 59 8.7N with

dimensions 26.3 km by 26.3 km. Near-infrared band 4 is shown in red, and visible red band 3 is shown in

cyan. (b) Reference labels derived from a RapidEye forest/nonforest classiﬁcation. Dark and light green are

≥50% forest cover. Yellow and orange are <50% forest cover. Dark green and yellow represent spatially homo geneous forest and nonforest labels, respectively. Light green and orange represent spatially heterogeneous

forest and nonforest labels, respectively. These mixed pixels constitute a 120-m buffer along forest/nonforest

interfaces. Forest accounts for 82.5% of the image and nonforest 17.5%. Near-infrared (a) (b) (c) R e d

FIGURE 9.3 (a) All forest and nonforest data from Figure 9.2, (b) forest and nonforest pixels greater than 60

m from forest/nonforest interfaces (pure population), and (c) forest and nonforest pixels within a 120-m buffer

along forest/nonforest interfaces (mixed population). Near-infrared (a) (b) (c)

R e

d

FIGURE 9.4 Results of (a) unsupervised clustering, (b) maximum likelihood, and (c) classiﬁcation tree algo

rithms on partitioning the red/near-infrared feature space for forest (shown in red) and nonforest (shown in cyan).

Green boundaries indicate forest, orange nonforest. For this test, all data were used as inputs. Near-infrared (a) (b)

R e

d

FIGURE 9.5 Example decision boundaries made using a classiﬁcation tree for (a) core site training dataset

and (b) mixed pixel training dataset. For each model, a 7% sample of forest and nonforest were drawn for

model generation from the populations shown in Figure 9.2b. Cyan represents nonforest and red represents

forest, based on Figure 9.2a.

FIGURE 10.4 Segmented image using a scale parameter of 125. Bare soil Cereal Burnt crop stubble Other highprotein crops

Woodlands and scrublands Urban soil 0

(a) (b) (c) 5 10 20 30 Kilometers Alfalfa

FIGURE 10.5 Example of comparison between QuickBird image (a), supervised classiﬁcation of the image

formed by the principal component and the NDVI index (b), and the oriented-based classiﬁcation (c). Bare soil Cereal Burnt crop stubble Other highprotein crops Alfalfa Woodlands and scrublands Urban soil 0 5 10 20 30 Kilometers

(a) (b) (c)

FIGURE 10.6 Example of comparison between QuickBird image (a), supervised classiﬁcation of the image

formed by the principal component and the NDVI index (b), and the HTM classiﬁcation (c). 2002 2003 2004 2005 2006

FIGURE 12.4 Example of wetland interannual spectral variability as seen in MODIS at 250-m spatial reso

lution, with bands displayed as red = band 2, green = band 6, and blue = band 1. (b) (c) (a)

FIGURE 14.1 Web-based interface used for GlobCover 2009 reference data collection by the international

expert network. Validation samples were automatically overlaid either in Virtual Earth or Google Earth (a),

combo boxes to characterize the samples with LCCS classiﬁers were included (b), and SPOT-VGT NDVI and

NDWI temporal proﬁles corresponding to the pixel displays as white square were provided (c). 10 max 20 max 30 max 40 max > 40

FIGURE 14.3 Number of valid MERIS FR surface reﬂectance observations for GlobCover 2005. 50 40 30 20 H e c t a r e s 10 0 50 4 3 2 1 0 40 30 20 H e c t a r e s 10 0 73 80 86 92 00 Ecoregion 1 Coast Range 73 80 86 92 00 Ecoregion 4 Cascades 73 80 86 92 00 Ecoregion 1 Coast Range 73 80 86 92 00 Ecoregion 2 Puget Lowlands 73 80 86 92 00 Ecoregion 3 Willamette Valley 73 80 86 92 00 Ecoregion 4 Cascades 73 80 86 92 00 Ecoregion 9 East Cascades 73 80 86 92 00 Ecoregion 77 North Cascades 73 80 86 92 00 Ecoregion 78 Klamath Mountains 73 80 86 92 00 Ecoregion 9 East Cascades 73 80 86 92 00 Ecoregion 77 North Cascades 73 80 86 92 00 Ecoregion

78 Klamath Mountains 73 80 86 92 00 Ecoregion 2 Puget Lowlands Average patch size of clear cuts (hectares) State boundary Overall Spatial LULC Change >25% 20%–25% 15%–20% North Cascades WASHINGTON OREGON O R E G O N C A L I F O R N I A Puget Lowlands <15% Coast Range Cascades Klamath Mountains East Cascades Slopes and Foothilis Wilamette Valley Shrub/scrub Grassland/herbaceous Pasture/hay Cultivated crops Woody wetlands Emergent herbaceous wetlands Barren land Forest Developed Snow/ice Open water Level III Ecoregions Patch density of clear-cuts (# per 1000 ha) 73 80 86 92 00 Ecoregion 3 Willamette Valley

FIGURE 15.1 The area shown covers seven ecoregions (Omernik, 1987; EPA, 1999) in the Paci�c Northwest of

the western United States, falling in California, Oregon, and Washington. The ecoregions are the Coast Range,

Puget Lowlands, Willamette Valley, Cascades, East Cascades, Slopes and Foothills, North Cascades, and Klamath

Mountains. All the ecoregions are primarily forested, with varying levels of agriculture, urban, and other land

uses. The map shows data from the 2001 National Land Cover Database (NLCD) (Homer et al., 2007) derived

from Landsat thematic mapper (TM) and enhanced thematic mapper plus (ETM+) data at a spatial resolution of

30 m. The pie charts represent two sources of important LULC data. Land-cover composition is characterized by

the relative size of each “wedge” and is based on NLCD data. The size of the pie charts re«ects the amount of land

that experienced changes in LULC as measured by the USGS Land Cover Trends project (Loveland et al., 2002).

The extent of land area that changed at least once between 1973 and 2000 varies considerably across the seven

ecoregions, including ecoregions with similar land-cover compositions. The changes in LULC re«ect variability in

the biophysical conditions, land ownership and management, and the impact of regional and national policy among

other drivers. LULC change data, such as those presented here, are most readily obtained through examination of historical satellite imagery and aerial photographs. The size and density of forest clear-cuts for the seven ecoregions

are displayed in a series of bar charts. Landscape metrics such as these are useful for a wide range of ecosystem

assessments and are immediately available through examination of remotely sensed data. Open water “A” - Business as usual “B” - Agricultural decline Projected 2020 land cover “C” - Agricultural expansion Wetland Urban and built-up Grassland Irrigated crop Dryland row crop Crops/mixed farming Hay/pasture Bare/fallow

FIGURE 15.2 Scenarios are a vital component of LULC modeling, allowing the exploration of multiple

possible futures and resultant impacts on ecological processes. Remote sensing both directly and indirectly

informs the construction of viable LULC scenarios through (1) construction of regional landscape histories,

(2) examination of LULC patterns, and (3) exploration of linkages between historical LULC change and

socioeconomic and biophysical driving forces. Each of these three components was used to develop sce

narios and model 2020 LULC for a portion of southwestern Kansas, in the central United States (Sohl et al.,

2007). Scenario A depicts a business-as-usual scenario. Scenario B depicts a scenario of low precipitation and

declining groundwater availability, leading to agricultural decline. Scenario C depicts a scenario of increased

precipitation and a more efficient utilization of groundwater, leading to agricultural expansion. The modeled

scenarios were used to examine the impacts of LULC change on regional weather and climate variability. Prairie Creek Redwoods State Park A A B D C B C D Prairie Creek Redwoods State Park Redwood National Park Redwood National Park Private Six Rivers National Forest August 29, 1987 August 12, 2010 Six Rivers National Forest Private

FIGURE 15.3 Two Landsat TM images acquired on August 29, 1987 (top) and August 12, 2010 (bottom).

Both images are of the same region in northern California, covering parts of Humboldt and Del Norte counties. The images use visible and near-infrared bands to depict vegetation in hues of red. Dense old-growth conifer stands appear dark red, whereas recent clear-cuts appear bright. Dimensionally, the images are approximately 30 km from east to west and 13 km from north to south. The images span three major land ownership types. Redwood National Park is in the west and is most easily recognized by the large contiguous stand of old growth redwoods found in Prairie Creek Redwoods State Park. In the eastern portion of the images is Six River National Forest (SRNF). SRNF is managed for multiple uses, including timber harvest. In the center of the image is a large swath of private land holdings along the Klamath River. Cutting on private lands generally occurs in relatively large, often contiguous patches, while SRNF is characterized by a smaller more dispersed pattern of cutting. No cutting is evident in the National Park. Cutting also seems to have accelerated in this area on both private and public lands. Satellite imagery, such as those presented here, are extremely useful for mapping and characterizing changes to landscapes, which provide the foundational understanding for LULC modeling efforts. In this example, land ownership is an important driver and constraint on LULC change and should be considered in any modeling effort.

TABLE 16.1

Twenty-Two Classes of the GlobCover Legend TABLE 16.3 Fourteen Classes of the GlobCorine Legend

160 Closed (>40%) broadleaved forest regularly flooded—fresh water

170 Closed (>40%) broadleaved semideciduous and/or evergreen forest regularly flooded—saline water

180 Closed to open (>15%) vegetation (grassland, shrubland, woody vegetation) on regularly flooded or waterlogged soil—fresh, brackish or saline water

190 Artificial surfaces and associated areas (urban areas >50%)

200 Bare areas

210 Water bodies

220 Permanent snow and ice

Value GlobCover legend

11 Post-flooding or irrigated croplands

14 Rainfed croplands

20 Mosaic cropland (50%–70%)/natural vegetation (grassland, shrubland, forest) (20%–50%)

30 Mosaic natural vegetation (grassland, shrubland, forest) (50%–70%)/cropland (20%–50%)

40 Closed to open (>15%) broadleaved evergreen and/or semideciduous forest (>5)

50 Closed (>40%) broadleaved deciduous forest (>5m)

60 Open (15%–40%) broadleaved deciduous forest (>5m)

70 Closed (>40%) needleleaved evergreen forest (>5m)

90 Open (15%–40%) needleleaved deciduous or evergreen forest (>5m)

100 Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)

110 Mosaic forest/shrubland (50%–70%)/grassland (20%–50%)

120 Mosaic grassland (50%–70%)/forest/shrubland (20%–50%)

130 Closed to open (>15%) shrubland (<5m)

140 Closed to open (>15%) grassland

150 Sparse (>15%) vegetation (woody vegetation, shrubs, grassland) Color Value GlobCorine legend 10 Urban and associated areas 20 Rainfed cropland 30 Irrigated cropland 40 Forest 50 Heathland and sclerophyllous vegetation 60 Grassland 70 Sparsely vegetated area 80 Vegetated low-lying areas on regularly flooded soil 90 Bare areas 100 Complex cropland 110 Mosaic cropland/natural vegetation 120 Mosaic of natural (herbaceous, shrub, tree) vegetation 200 Water bodies 210 Permanent snow and ice Color 10 max 20 max 30 max 40 max > 40

FIGURE 16.5 Number of valid observations obtained after 19 months of MERIS FRS acquisitions. Magenta

areas are defined as well covered (>40 observations). 1 6 5 15 16 13 14 12 11 10 9 7 8 17 18 20 19 21 22 4 3 2

FIGURE 16.7 Overview of the 22 equal-reasoning areas used as stratification.

FIGURE 16.8 The GlobCover 2005 product as the first 300-m global land-cover map for the period

December 2004–June 2006.

FIGURE 16.9 Improvement of the spatial detail due to the use of a 300-m spatial resolution. Deforestation

clear-cuts in Amazonia (top), irrigated crops in Saudi Arabia's desert (center), and specific vegetation structure

in Russia (bottom). GLC2000 (left), GlobCover (center), and Google Earth (right). Number of acquisitions (January–December 2009) 0 1-5 6-10 11-50 51-100 101-200 201-300 > 300

FIGURE 16.10 MERIS FRS density data acquisition over the year 2009.

FIGURE 16.11 The GlobCover 2009 product as the first 300-m global land-cover map for the year 2009.

FIGURE 16.14 GlobCorine 2005 land-cover map.

FIGURE 16.15 The classification of Norway (right), which was not covered by the reference database (left),

proved to be spatially consistent with surrounding areas.

FIGURE 16.17 The GlobCorine 2009 product.

SPOT VEGETATION

Clean NDVI &

NDWI profiles

Clustering/labeling Clustering/labeling Closed vegetation (forest, woodland...) Open vegetation

(grassland and shrubland) Swamp forest Urban areas Montane forest Bare soil (rocks and sands) �reshold on texture �reshold/classification �reshold on altitude �reshold SPOT VEGETATION Monthly color composite Radar (ERS, JERS) DMSP Night time lights SRTM Albedo

FIGURE 17.1 Datasets and main classi�cation algorithms used in the production of the GLC2000 map of

Africa. (From Mayaux, P. et al., J. Biogeogr., 31, 861–877, 2004. With permission.)

(a)

(b) Legend Irrigated croplands Rainfed croplands Mosaic croplands/vegetation Mosaic vegetation/croplands Closed to open broadleaved evergreen or semideciduous forest Closed broadleaved deciduous forest Closed needleleaved evergreen forest Open needleleaved deciduous or evergreen forest Closed to open mixed broadleaved and needleleaved forest Mosaic forest-shrubland/grassland Mosaic grassland/forest-shrubland Closed to open shrubland Closed to open grassland Sparse vegetation Closed to open broadleaved forest regularly flooded (fresh-brackish water) Closed broadleaved forest permanently flooded (saline-brackish water) Closed to open vegetation regularly flooded Artificial areas Bare areas Water bodies Permanent snow and ice Open broadleaved deciduous forest

FIGURE 17.3 (a) (Top) Globcover classi�cation over Africa (2005–2006) and legend; (b) (bottom) compari

son of the GLC2000 map (left) with the Globcover map (right) over Senegal, Guinea-Bissau, and Gambia. Cities Closed deciduous forest Cropland Dense forest Edaphic forest Mangroves Mosaic forest/Savanna Others Rural complex Waterbodies

FIGURE 17.5 Detail of the fusion map over the northern part of the Congo Basin at the borders between

Cameroon, Gabon, Congo, Central African Republic, and Democratic Republic of Congo. 800 Average Rainfall Hyderabad Chittagong Udon ani Saigon Chittagong Udon ani Saigon Balikpapan Aceh Jakarta Balikpapan Aceh Jakarta Bengaluru New Delhi Chennai Mumbai Hyderabad Bengaluru New Delhi Chennai Mumbai South Asia Average Temperature South Asia Average Temperature Cont. SE Asia Average Temperature Insular SE Asia 700 600 500 400 300 200 100 0 40 °C 35 30 25 20 15 10 40 °C 35 30 25 20 15 10 40 °C 35 30 25 20 15 10 1 2 3 4 5 6 7 8 Month 9 10 11 12 800 700 600 500 400 300 200 100 0 1 2 3 4 5 6 7 8 Month 9 10 11 12 800 700 600 500 400 300 200 100 0 1 2 3 4 5 6 7 8 Month 9 10 11 12 1 2 3 4 5 6 7 8 Month 9 10 11 12 1 2 3 4 5 6 7 8 Month 9 10 11 12 1 2 3 4 5 6 7 8 Month 9 10 11 12 Average Rainfall Insular SE Asia Average Rainfall Cont. SE Asia

FIGURE 18.1 Rainfall and temperature patterns in the main subregions of tropical Asia. (From Arino, O.

et al., Eur. Space Agency Bull., 136, 24–31, 2008. With permission.) 60°E 80°E 100°E 120°E 140°E 1 0 ° S 1 0 ° N 3 0 ° N Coniferous mountain forest, evergreen Temperate mountain forest, broadleaved evergreen Tropical and subtropical mountain forest, broadleaved evergreen Tropical lowland forest, broadleaved evergreen Tropical mixed deciduous and dry deciduous forest Mangrove forest Swamp forest and woodland Forest mosaics/Fragmented or degraded forests Evergreen shrubland and regrowth/Low intensity or abandoned shifting cultivation Deciduous shrubland/Mosaics of deciduous shrub cover and cropland Deciduous thorny scrubland Grasslands on plains and slopes Sparse grassland Alpine grassland Sparse shrub and grassland Shifting cultivation/Mosaics of cropping and natural vegetation Mixed cropland and plantations Cropland Cropland, irrigated, inundated or flooded Bare soils Rocks Temporarily flooded areas Ice and snow Urban areas Water bodies Sea No data

FIGURE 18.2 Land-cover map of the Lower Mekong Basin. (From FAO, Forest Resources Assessment

1990—Tropical Countries. FAO Forestry Paper 112, Rome, 1993. With permission.) China Myanmar ailand N 0 100 200 Kilometers Vietnam Evergreen forest dense Wood + Shrubland evergreen Wood + Shrubland dry Wood + Shrubland inundated Shifting Cultivation <30% cropping Shifting Cultivation >30% cropping Agriculture Barreb Land Rock Urban Water

Wetland Other Cloud Grassland Bamboo Evergreen forest open Evergreen forest fragmented Semi-evergreen forest dense Semi-evergreen forest open Semi-evergreen forest fragmented Deciduous forest Deciduous forest fragmented Forest regrowth Forest regrowth, inundated Inundated forest Inundated forest, fragmented Mangrove forest Forest plantations Other forest

FIGURE 18.3 Land-cover map of the Lower Mekong Basin. (From Martimort, P. et al. Eur. Space Agency

Bull. 131, 19–23, 2007. With permission.) CORINE Land Cover 2006 Prepared by GISAT, 2010 1200 N 0 200 400 600 800 1000 Kilometers 111 112 121 122 123 124 131 132 133 141 142 211 212 213 221 222 223 231 241 242 243 244 311 312 313 321 322 323 324 331 332 333 334 335 411 412 421 422 423 511 512 521 522 523 Countries not covered

FIGURE 19.3 The spatial distribution of 44 CLC land-cover classes of Europe for the year 2006. Mean area = 31.69 ha 1.00 - 31.68 31.69 - 696.00 Countries covered Countries not covered LCF2 area in 3km grid [ha] 0 1200200 400 600 800 1000 Kilometers Prepared by GISAT, 2010 N

FIGURE 19.5 Spatial distribution of intensi�cation of agriculture in European countries in 2000–2006. Mean area = 19.73 ha 1.00 - 19.72 19.73 - 599.00 Countries covered Countries not covered LCF1 area in 3km grid [ha] 0 1200200 400 600 800 1000 Kilometers Prepared by GISAT, 2010 N

FIGURE 19.4 Spatial distribution of urbanization in European countries in 2000–2006. January February March April May June July August September October November December

FIGURE 20.1 North America top-of-the-atmosphere re«ectance monthly composites from MODIS/Terra

2005 at 250-m spatial resolution. Before edgematch (a) (b) Before edgematch After edgematch After edgematch

FIGURE 20.3 Examples of matching cross-border land-cover data (a) the U.S.–Mexico and (b) Canada–U.S.

border before and after edge-matching procedure.

FIGURE 20.5 Land-cover map of North America 2005 at 250-m spatial resolution.

FIGURE 21.1 Trans-Amazonian highway (BR163) at the north of Pará state. Mosaic of SPOT VGT data

(left) and mosaic of MERIS FR data (right). 250 200 150 100 50 0 Spatial profile D a t a v a l u e 7500 6500 5500 5000 1000 2000 3000 Location Spatial profile 4000 D a t a v a l u e 6000 7000

(a) (b)

(c) (d) Location 1000 1500 2000 2500 3000 3500500

FIGURE 21.2 Top: MERIS image before (a) and after (b) applying cross-track illumination correction.

Bottom: spatial pro�le of the spectral band 2 from a transect of the same image before (c) and after (d) apply

ing cross-track illumination correction. Legend Evergreen forest Dry forest Shrub Grassland Sparse or barren Water Snow and ice Agriculture mosaic Agriculture

FIGURE 21.4 The �nal land-cover MERIS map.

FIGURE 21.6 A 200 km by 150 km extract from the MERIS (left) and GLC2000 (right) maps along the

Trans-Amazonian highway in Brazil. Agriculture is represented in gray and light green and forest in darker

green.

FIGURE 21.7 Extract of Rondônia showing the agricultural expansion in yellow from GLC2000 (a) and

MERIS 2009/2010 (b). The forest cover is in green and savannahs in red. 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 –

60 60 – 80 80 – 100 100˚E 110˚E 120˚E (a) (b) (c) (d) (e) (f) 90˚E 100˚E 110˚E 120˚E 90˚E 100˚E 110˚E 120˚E 90˚E 100˚E 110˚E 120˚E 90˚E 100˚E 110˚E 120˚E 90˚E 100˚E 110˚E 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 70˚E 80˚E 90˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 100˚E 110˚E 120˚E 130˚E 140˚E 70˚E 80˚E 90˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 100˚E 110˚E 120˚E 130˚E 140˚E 70˚E 80˚E 90˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N

FIGURE 22.3 Spatial patterns of land-cover and land-use changes in China from the late 1980s to the late

1990s: (a) Cultivated land, (b) forest area, (c) grassland, (d) water area, (e) built-up area, and (f) unused land. 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 100˚E 110˚E (a) (b) (c) (d) (e) (f) 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 100˚E 110˚E 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 100˚E 110˚E 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 100˚E 110˚E 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 70˚E 80˚E 90˚E 90˚E –100 – –80 Percent change –80 – –60 –60 – –40 –40 – –20 –20 – –10 –10 – 10 10 – 20 0 250 500 1000 km 20 – 40 40 – 60 60 – 80 80 – 100 100˚E 110˚E 120˚E 100˚E 110˚E 120˚E 130˚E 140˚E 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N 5 0 ˚ N 2 0 ˚ N 3 0 ˚ N 4 0 ˚ N

FIGURE 22.4 Spatial patterns of land-cover and land-use changes in China from the late 1990s to the mid

2000s: (a) Cultivated land, (b) forest area, (c) grassland, (d) water area, (e) built-up area, and (f) unused land.

FIGURE 23.3 Ecoregional distribution of the 20-km × 20-km sample blocks selected for the first nine com

pleted ecoregions and the subsequent 10-km × 10-km sample blocks selected for the remaining 75 ecoregions

of the conterminous United States. MSS February 6, 1973 MSS June 26, 1979 A B B A

FIGURE 23.4 The definition for the “mechanically disturbed” LULC class accommodates a range of vari

ance in land-cover conditions to support the conceptual intent of the project. In this sample block from the

Ouachita Mountains ecoregion, Areas “A” and “B” were mature forests in 1973. The subsequent image for

1980 era reveals Area A as recently disturbed and unvegetated and Area B as vegetated but obviously altered

since 1973. FOOTPRINT % 0–2.5 2.5–5 5–6.5 6.5–8 8–10 10–15 15–34

FIGURE 23.5 Estimates of the total spatial extent, or footprint, of land-cover change for the 84 ecoregions

of the conterminous United States. Changed area (000 ha) 1975–2000 Land-cover class Forest Natural nonforest vegetation Agriculture Barren Water 0–50 50–100 100–2000 2000–4000 4000–6000 6000–8000 8000–12,000 12,000–14,000 Loss Gain

FIGURE 24.2 Distribution and proportion of land-cover changes between 1975 and 2000. The top image

represents the loss of land cover, whereas the bottom image shows the gain in land cover. The size of the pie

chart corresponds to the extent of area changed. Land-surface climate interaction Vegetation characteristics Weather Change environmental condition Services+accounting Ecosystems Cultivation pattern+forestry Land degradations Agriculture Ecosystem characteristics Habitats+fragmentation Biodiversity Fire monitoring Land degradation assessment Disasters Land change/disease

Vectors/boundary condition Health Bioenergy/biomass Wind/hydropower assessment Energy Land change and greenhouse gas emission Water+energy exchanges Climate Water resources/quality Land- +water-use pattern Water

FIGURE 26.3 GEO areas of societal bene�ts and key land-cover observation needs emphasize the multitude

of services from continuous and consistent global terrestrial observations.

100,000

10,000

1000

100 10 1 Resolution used in current models Resolution required to improve current models Resolution required in new modeling approaches Key users Associate users Required for modeling Required for parameter estimation Required for land-cover change detection Broad users Key users Key users

[m

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l o

g)

FIGURE 26.5 Spatial resolution median requirements (note y-axis in log-scale) from user surveys. The

orange points indicate the minimum requirement.